CLAIMS

1. A method of interactively simulating contact between a deformable first object (201; 20; 40; 60; 80) and a second object (202; 30; 50; 70; 90; 91) using a simulated model with a predetermined sampling time step, the method being characterized in that:

(a) the parameters describing the physical characteristics of each of the objects, such as the geometry and the mechanics of the materials of each of the objects, are calculated beforehand and stored in a memory,

(b) at the beginning of each sampling time step of the simulated model, a real-time analysis of the inherent behavior of each object is carried out at the level of each object in order to predict the positions, speeds and accelerations of that object in application of a free movement that does not take account of any subsequent contacts,

(c) in each sampling time step of the simulated model, pairs of objects that are detected as intersecting are analyzed in real time at the level of an overall scene including the objects liable to come into contact, and a list of groups of collisions is established that contains a string of objects in collision and a description of the collisions,

(d) in each sampling time step of the simulated model, parameters representing the physical characteristics of the objects and the description of the collisions are repatriated in real time for each group of collisions to determine, for each instance, the solution to the Signorini problem that governs contact between two objects in the case of pure relative sliding,

(e) at the end of each sampling time step of the simulated model, a real-time display of the inherent behavior of the object following the collision is effected at the level of each object, and

(f) all real-time processing is effected with a computation time step shorter than the sampling time step of the simulated model so as to define an interactive simulation in which the user can intervene directly during simulation.

2. A method according to claim 1, characterized in that during the step a) of calculating beforehand parameters describing the physical characteristics of each of the objects, a finite element type description of deformations is used for the parameters describing the mechanics of the materials, with matrices being filled and inverted, systems of equations being solved, and data being stored in memory.

3. A method according to claim 1 or claim 2, characterized in that each object is described in a rest configuration as a set of triangles reproducing its surface and a set of tetrahedra describing the interior of the object.

4. A method according to claim 3, characterized in that each triangle is described by three points placed in an order such that normals are calculated that are invariably directed towards the exterior of the object.

5. A method according to claim 3 or claim 4, characterized in that the deformations of the objects are interpolated by the finite element method using a linear tetrahedral mesh.

6. A method according to any one of claims 1 to 5, characterized in that in each computation time step the explicit forces applied to an object, which are already known at the start of the computation step, are integrated during the step b) at object level to define the movements of the object that they generate, whereas the values of the implicit contact forces, which depend on the movement of the objects in

the computation time step, are determined during the step d) of seeking the solution to the Signorini problem at the level of an overall scene.

7. A method according to any one of claims 1 to 6, characterized in that during the step c) of analysis at the level of an overall scene, the existing intersections between the objects of the scene are detected geometrically in order to extract from pairs of elements of intersecting objects a length and a direction of interpenetration between the two elements of a pair of elements of objects.

8. A method according to claim 7, characterized in that during the step c) of analysis at the level of an overall scene, to extract from pairs of elements of intersecting objects a length and a direction of interpenetration between the two elements of a pair of elements of objects, an intermediate movement of the objects between the preceding computation step and the current computation step is also taken into account in order to compute a preferential direction of interference between the objects.

9. A method according to any one of claims 3 to 5, and according to claim 7, characterized in that during the step d) of seeking the solution to the Signorini problem, the extreme points of application of the contact force between the two objects in collision are reconstructed if those extreme application points have not been determined during the preceding step.

10. A method according to claim 9, characterized in that during the step d) of seeking the solution to the Signorini problem, in the case of a segment-segment intersection of two triangular objects (40, 50), the two points (41, 51) selected

to constitute the extreme points of application of the contact force between the two objects (40, 50) in collision are situated at the intersection of each of the two segments (P_1P_2, Q_1Q_2) with the plane formed by the face of the triangle in the intersection.

11. A method according to claim 9, characterized in that during the step d) of seeking the solution to the Signorini algorithm, in the case of a point-face intersection of two triangular objects (60, 70), a first point (71) selected to constitute a extreme point of application of the contact force between the two objects (60, 70) in collision is the point of the intersection whereas the second extreme point of application of the contact force between the two objects in collision is the projection (61) of the first extreme point (71) onto the face of the triangle (60) in the intersection.

12. A method according to any one of claims 9 to 11, characterized in that barycentric coordinates are used to distribute the displacements and the forces of the points of application of the contact force between the extreme points of application of the contact force by effecting a linear interpolation for a finite element modeling process.

13. A method according to claims 10 and 12, characterized in that the distance δ of interpenetration between the two extreme points (41, 51) of application of the contact force in the case of a segment-segment contact between a first segment (Q_1 Q_2) and a second segment (P_1 P_2) of a second triangle is calculated from the following equation:

$$\delta = [a_i \;\; b_i \;\; c_i] \left[[\alpha \;\; 1 - \alpha] \begin{bmatrix} W_1 \\ W_2 \end{bmatrix} - [\beta \;\; 1 - \beta] \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \right] \quad (1)$$

in which:

α and $1 - \alpha$ are the barycentric coordinates on the first segment (Q_1 Q_2)

β and $1 - \beta$ are the barycentric coordinates on the second segment (P_1 P_2),

a_i b_i c_i are the coordinates of the interpenetration direction n_i,

W_1 and W_2 are the coordinates of the first segment Q_1 Q_2, and

V_1 and V_2 are the coordinates of the second segment P_1 P_2.

14. A method according to claims 11 and 12, characterized in that the distance δ of interpenetration between the two extreme points (61, 71) of application of the contact force in the case of a point-plane contact between a point (71) of a second triangle and a plane (P_1 P_2 P_3) of a first triangle is calculated from the following equation:

$$\delta = [a_i \;\; b_i \;\; c_i] \left[[\alpha \;\; \beta \;\; \gamma] \begin{bmatrix} W_1 \\ W_2 \\ W_3 \end{bmatrix} - V_1 \right] \quad (2)$$

in which:

α, β and γ are the barycentric coordinates on the first triangle,

a_i b_i c_i are the coordinates of the interpenetration direction n_i,

W_1, W_2, W_3 are the coordinates of the first triangle (P_1 P_2 P_3),

V_1 represents the coordinates of the point of contact consisting of a vertex (Q_1) of the second triangle (Q_1 Q_2 Q_3)..

15. A method according to any one of claims 1 to 14, characterized in that when the points of application of the contact forces between two objects in collision have been determined, during the step d) the mechanical characteristics of the objects are transferred into the defined contact space

in which the whole of a group of m contacts with n objects is processed, where m and n are integers.

16. A method according to claim 15, characterized in that during the step d) the mass and inertia of an object are considered lumped together at its centre of mass and an instantaneous relationship between the contact forces f_c in the contact direction, the accelerations δ''_c caused by the constraints in the same direction, and the free accelerations δ''_{free} in the same direction known during the step c) at the level of an overall scene is established from the equation:

$$\delta''_c = J_c M^{-1} J_c^T f_c + \delta''_{free} \quad (3)$$

in which:

J_c is an m*6n Jacobean matrix that transfers the instantaneous linear and angular movement into the contact space,

J_c^T is the transposed matrix of J_c,

M is a block diagonal matrix corresponding to the mass and inertia of the n objects of the group of contacts.

17. A method according to any one of claims 9 to 14 and either of claims 15 and 16, characterized in that during the step d), to transport the local mechanical characteristics, a relationship is established between:

the displacement difference (U_k^i) of the points of the deformable mesh representing the object i at the time k, between the free deformation ($U^i_{k.free}$) and the constrained deformation ($U^i_{k,c}$), in other words $U_k^i = U^i_{k,c} - U^i_{k,free}$

the free and constrained relative positions δ_{free} and δ_c of the objects in the contact space:

$$\delta = \Sigma_{I=1}^{n} N_c^i U_k^i + \delta_{free} \quad (4)$$

where N_c^i is a matrix for passing from the displacement space of the mesh to the displacement space of the contacts, and

a relationship is established between the forces in the contact space f_c and the forces in the deformation forces space F_k:

$F_k = (N_c^i)^T f_c$ (5)

18. A method according to claim 1, characterized in that during the step d) an instantaneous linear relationship characterizing contact deformations or displacements δ_c from the contact forces f_c and the free displacements δ''_{free} caused by free movements integrating only the forces known explicitly at the beginning of the computation time step is established from the following equation:

$\delta_c = \left[\Sigma_{i=1}^{n} N_c^i A (U_{k-1}) (N_c^i)^T \right] f_c + \delta_{free}$ (6)

in which:

N^i_c is a matrix for passing from the displacement space of the mesh to the displacement space of the contacts,

$(N^i_c)^T$ is the transposed matrix of N^i_c,

A is a matrix defining the deformation of the object at the local level, such that if U_k represents the vector of the displacement in the local frame of reference of the object at the current time and U_{k-1} represents the displacement vector in the local frame of reference of the object in the preceding calculation step, the instantaneous values whereof are known at the beginning of the current computation step, then:

$U_K = A (U_{k-1}) F_k + b (U_{k-1})$ (7)

where:

F_k is a vector representing the external forces applied to the object expressed in the local frame of reference, and

b is a vector that has a value in the displacement space and depends on the object deformation model.

19. A method according to claim 17, characterized in that during the step d) an instantaneous relationship

characterizing the contact deformations or displacements δ_c from the contact forces f_c and the free displacements δ''_{free} caused by free movements integrating only the forces known explicitly at the beginning of the computation time step is established from the following equation:

$$\delta_c = \left[\theta\, dt^2 J_c M^{-1} J_c^{\ T} + \Sigma_{i=1}^{n} N_c^{\ i} A\, (U_{k-1})\, (N_c^{\ i})^T\right] f_c + \delta_{free} \quad (8)$$

in which:

J_c is an m*6n Jacobean matrix that transfers the instantaneous linear and angular movement into the contact space,

J_c^T is the transposed matrix of J_c,

M is a block diagonal matrix corresponding to the mass and inertia of the *n* objects of the group of contacts,

θ is a constant depending on the time integration method,

N^i_c is a matrix for passing from the displacement space of the mesh to the displacement space of the contacts,

$(N^i_c)^T$ is the transposed matrix of N^i_c,

A is a matrix defining the deformation of the object at the local level such that if U_k represents the vector of the displacement in the local frame of reference of the object at the current time and U_{k-1} represents the displacement vector in the local frame of reference of the object in the preceding calculation step the instantaneous values whereof are known at the beginning of the current computation step, then:

$$U_K = A\ (U_{k-1})\ F_k + b\ (U_{k-1}) \qquad (7)$$

where:

F_k is a vector representing the external forces applied to the object expressed in the local frame of reference, and

b is a vector that has a value in the displacement space and depends on the object deformation model.

20. A method according to any one of claims 1 to 19, characterized in that it further comprises a step of coupling

with a haptic interface module to produce haptic sensation feedback to a mechanical system by means of which an operator manipulates the objects in a virtual scene.

21. A system for the interactively simulating contact between a deformable first object (201; 20; 40; 60; 80) and a second object (202; 30; 50; 70; 90; 91) using a simulated model with a predetermined sampling time step, the system being characterized in that it comprises:

(a) a module (100) for calculating beforehand parameters describing the physical characteristics of each of the objects, such as the geometry and the mechanics of the materials of each of the objects,

(b) a memory (102) for storing parameters previously calculated in the computation module (100),

(c) a coupling module (101) to a user interface (104) comprising a mechanical system held by a user to exert virtual forces on said objects in a scene of the simulated model,

(d) a display screen (107) for displaying said objects represented in the form of meshes,

(e) a central processor unit (100) associated with input means (103), comprising at least:

e1) an object analysis module for analyzing in real time at the level of each object the inherent behavior of the object in order to predict the positions, speeds and accelerations of that object in application of a free movement that does not take account of any subsequent contacts,

e2) an analysis module for an overall scene including the objects liable to come into contact, for analyzing in real time pairs of objects that are detected to be interacting and to establish a list of groups of collisions that contains a string of objects in collision and a description of the collisions,

e3) a module for the real time repatriation, for each group of collisions, of the parameters representing the physical characteristics of the objects and the description of the collisions, for determining, for each instance, the solution to the Signorini problem that governs contact between two objects in the case of pure relative sliding,

e4) a module for processing each object for real time display at the level of each object of the inherent behavior of that object following a collision, and

e5) means for determining a computation step shorter than the sampling time step of the simulated model so as to define an interactive simulation.

22. A system according to claim 21, characterized in that it comprises means for producing haptic sensation feedback to the user interface (104).

23. A system according to claim 21 or claim 22, characterized in that the computation step corresponds to a frequency greater than or equal to approximately 500 Hz.